Indian J. Phys. **51A**, 80–87 (1977)

Alpha-preformation probability in even-even nuclei: A new approach

M. K. Basu

Department of Physics, University College of Science, Calcutta-700009

(*Received* 23 *April* 1976)

A comparative study of experimental and present theoretical α-preformation probabilities in even-even nuclei reveals that experimental preformation probability is correct so far as the order of magnitude is concerned and that the present theoretical method of *α-decay without tunnelling* origin is a very accurate method for the evaluation of α-preformation probability in even-even nuclei. It is, moreover, found that this probability is a decreasing function of target-mass and that shell and sub-shell closure, and deformation in nuclear shape have a very pronounced effect on its absolute magnitude. The range of α-preformation probability predicted for almost all even-even nuclei is between 0·6 and 0·1 in close accord with experimental observations.

1. Introduction

Present-day great interest in the alpha-preformation probability (P_α) is mainly due to the fact that precise knowledge of this important physical parameter provides a sound basis to a clear understanding of the mechanism of natural α-emission and, other α-emission, α-pick-up and α-transfer reactions. α-preformation is, in fact, a four-body problem in a many-body system, which makes its study really difficult. Consequently there exists a wide gap between theory and experiment. Attempts so far made at the theoretical evaluation of its absolute value are few in number and have yielded, as is well-known (Hanna 1959), widely divergent values ($\sim 10^{-1}$ - 10^{-5}) of P_α. Consequently such attempts are almost abandoned and the existing trend is, instead, to present P_α qualitatively in the form of reduced α-decay width (Rasmussen 1959; Hanna 1959; 1977) Mang 1964; Harada & Rauscher 1968; Fliessbach 1975). But unfortunately it is impossible to decipher the absolute α-preformation probability from the reduced decay-width; this is one of the weakest points of Gamow theory of α-decay. Recently Basu (1974), in this picture of *α-decay without tunnelling*, has come across a very simple theoretical expression for P_α which has later (Basu 1976, 1977) been found very accurate compared to the experimental P_α determinations. Attempts at its experimental determinations are very recent and a clear qualitative and quantitative picture of alpha-preformation probability for different nuclei is gradually evolving out of the results of last 3–4 years' experiments. Colli and his co-workers (Colli-Milazzo & Braga-Marcazzan 1972, 1973, 1973;

Braga-Marcazzan *et al* 1973; Colli-Milazzo *et al* 1974, 1975) have obtained a consistent set of P_α values in the range of 0·03 0·7 through the alpha-preformed pre-equilibrium analyses of (n, α) and (P, α) reaction cross-sections. A set of P_α values in the range of 1·0–0·01 has also been extracted by Bonetti & Milazzo-Colli (1974) from experimental α-decay rates of spontaneous α-emitters in the light of Weisskopf's statistical hypothesis of α-decay. Another set of consistent values lying between 0·1 and 0·2 has very recently been obtained by Chevarier *et al* (1975) from the cross-section data of α-emission reactions induced in different nuclei through different incident channels. Notwithstanding the consistency, the experimental P_α values are uncertain in that these have been extracted from the reaction data by treating the α-preformation probability as a freely adjustable parameter in the fitting procedure which consequently absorbs other vagaries of the theory. Besides this, the inaccuracy of the experimental input data (reaction cross-section) is also quite considerable. P_α, derived from the statistical hypothesis of α-decay, is also of limited accuracy due to the uncertainty in the transmission factor calculation. Moreover, the accuracy of these values cannot be checked for lack of any reliable reference data. One, therefore, feels uncertain about the degree of confidence to be attached to these experimental values

The purpose of this article, already briefly reported (Basu 1976), is to survey experimental P_α determinations to-date and then to compare these with the present evaluations in order to assess the relative merits of different approaches. Target-mass dependence, in general, and shell-structure and deformation dependence, in particular, of P_α will also be critically investigated and qualitatively explained. Only even-even nuclei will be considered in this study.

2. Theory

It has been clearly demonstrated by Basu (1974) and, Basu & Sen (1975) that last two neutrons and last two protons are the constituents of the α-particle emitted by even-even α-emitters. This finding lends credence to the hypothesis (Wilkinson 1961; Clark & Wang 1966; Brink & Castro 1974) that α-clusters are formed in the low-density nuclear surface region where Pauli exclusion principle is less stringently operative than in the nuclear interior. Last $2n-2p$ system as an α-cluster in the surface region again fits well into the direct surface knock-out mechanism which forms the main basis of the α-preformed pre-compound analysis of reaction data for extracting P_α for different target nuclei.

The following expression for α-preformation probability was obtained in the theory of α-decay without tunnelling (Basu 1974).

$$P_\alpha = E_{CI}{}^\alpha/B(\alpha) \qquad \ldots \quad (1)$$

where $E_{CI}{}^\alpha$ = effective p-clustering energy of the last $2n$–$2p$ system. $B(\alpha)$ = Binding energy of a free α-particle.

It should be pointed out in this connection that alpha-preformation signifies a particular configuration of the last $2n$–$2p$ system in the ground state of as nucleus irrespective of whether the nucleus is α-active or not, and as such, its probability should be independent of the mode of α-emission and the theory thereof. This very stringent criterion is well satisfied by the expression in eq. (1) which, for its evaluation, depends only on the binding-energy data necessary for the calculation of $E_{CJ}{}^{\alpha}$. Unlike in the present case, P_α (Expt.) values, referred to already, owe their evaluations to the particular theory of α-emission and, consequently, are not free from the uncertainty of the theory as also from the inaccuracy of the experimental data. With this distinction clear in mind, one can probably better assess the merit of the present approach relative to experimental determinations.

The measured reduced α-decay widths (δ^2) (Rasmussen 1959) for an even-even isotopic series, as already pointed out in a previous work (Basu & Sen 1975), exhibit qualitatively the same behaviour as present P_α and are, in that sense, proportional to the absolute α-preformation probability.

3. Results and Discussion

In table 1 is shown P_α (Theor.) (Present evaluation) along with P_α (Expt.) (Pre-equilibrium) of those even-even nuclei for which P_α (Expt.) has been explicitly given in existing literature. No attempt has, however, been made to read out P_α (Expt.) from the experimental plots (Colli-Milazzo & Marcazzan-Braga 1973; Colli-Milazzo *et al* 1974, 1975), as it involves complete uncertainty regarding the identification of the corresponding nucleus.

One finds from table-1 that the agreement between P_α (Theor.) and P_α (Expt.) is quite nice and the individual discrepancy is seldom greater than a factor of two. Even if one considers P_α (Expt.) of all the even-even nuclei in the iexperimental plots, one can safely put a maximum limit of discrepancy at a factor of three. Notwithstanding this factor-of-three discrepancy, the agreement should be considered very encouraging in view of the fact that this puts an end to the wide difference of opinions about the order of magnitude ($\sim 10^{-1}$–10^{-5}) of the α-preformation probability. Now obviously the source of discrepancy cannot lie in the evaluation of P_α (Theor.) as $E^\alpha{}_{CJ}$ can be computed with the greatest possible accuracy from the mass relation due to Basu (1972) with the help of the mass evaluations (Wapstra & Gove 1971). Again P_α (Expt.) values are, as the authors themselves point out, uncertain. As already pointed out, P_α (Expt.) has, in fact, been treated as a freely adjustable parameter in the pre-compound analysis of the reaction data. Consequently it cannot be free from the uncertainties of the reaction theory, besides being uncertain due to the inaccuracy of the experimental input data. The near agreement between P_α (Theor.) and P_α (Expt.) together with the fact that P_α (Theor.) is, as pointed

Table 1. Comparative study of P_α (expt.) and P_α (theo.)

Source	Target nucleus	Type of reaction	P_α (Expt.)	P_α (Theor.)
Chevarier *et al* (1975)	$^{64}Fe_{26}$	(P, α)	0·16, 0·12	0·29
	^{56}Fe	(d, α)	0·12	0·26
	$^{66}Zn_{30}$	(P, α)	0·14	0·26
	$^{118}Sn_{50}$	(P, α)	0·16	0·24
	^{120}Sn	(P, α)	0·16	0·25
	$^{206}Pb_{82}$	(α, α')	0·80	0·15
Colli-Milazzo *et al* (1974)	$^{152}Sm_{62}$	(P, α)	0·45	0·21
	^{154}Sm	(P, α)	0·32	0·17
	$^{150}Nd_{60}$	(P, α)	0·44	0·20
	$^{176}Yb_{70}$	(P, α)	0·20	0·13
	$^{194}Pt_{78}$	(P, α)	0·12	0·17
	^{196}Pt			0·16
Colli-Milazzo & Marcazzan-Braga (1973)	$^{168}Er_{68}$	(n, α)	0·19	0·14
Colli-Milazzo *et al* (1975)	$^{140}Ce_{58}$	(P, α)	0·08	0·17
	$^{150}Sm_{62}$	(P, α)	0·22	0·19
	$^{156}Gd_{64}$	(P, α)	0·26	0·17
	$^{206}Pb_{82}$	(P, α)	0·065	0·15
	^{202}Pb	(P, α)	0·05	0·127
			0·04	
	$^{232}Th_{90}$	(P, α)	0·35	0·157

out already, independent of the theory of α-emission establishes the expression (1) as a very accurate expression for the theoretical evaluation of α-preformation probability for any even-even nucleus.

It is to be noted from table-1 that P_α (Expt.) = 0·8 for ^{206}Pb due to Chevarier *et al* is in gross error as already pointed out by Basu (1976). The latest experimental determination, due to Colli-Milazzo *et al* (1975) put P_α (Expt.) = 0·065 for ^{206}Pb which is very much nearer to the present theoretical evaluation.

P_α (Expt.), determined from Weisskopf's statistical hypothesis of α-decay (Bonetti & Milazzo-Colli 1974), lies in the range of 1·0–0·01 quite contrary to the ranges 0·21–0·08 and 0·5–0·02 of P_α obtained by the present calculation and the latest precompound analysis, respectively, for the same range of nuclei

(A = 150-209). Obviously the statistical approach over-estimates this parameter to a great extent. This overestimation is all the more glaring in the case of heavy nuclei for which this approach yields $P_\alpha \approx 1$ which cannot be accepted, not only in the light of results of present calculation and pre-compound analysis, but also on the ground of the following theoretical considerations. One expects highest α-preformation probabilities only in the case of light alpha-nuclei (Basu 1972) in which last two neutrons and last two protons, constituents of the α-cluster, are in the same orbit, enjoy maximum orbital symmetry and, consequently maximum overlap of their wavefunctions. In all other nuclei, particularly in heavy α-active nuclei, last two neutrons and last two protons which have a very poor overlap of their wavefunctions consequent upon their being in different orbits frequently belonging to different major shells, are, of necessity, constrained to be in a very low state of α-preformation. This conclusion is well confirmed by the P_α values of the present approach and of the α-preformed pre-equilibrium analysis. Overestimation in the statistical approach may be due to the uncertainty in the choice of values for the single-particle level-density, error in the calculation of the transmission factor caused by the arbitrariness in the choice of the decay-radius as pointed out previously (Basu & Sen 1975) and lastly due to the inherent limitation of the statistical hypothesis of α-decay

4. Mass-Dependence of and Shell-Closure Evidences in P_α

To study the mass-dependence of the α-preformation probability, P_α (Theor.) has been plotted versus neutron-number in Fig. 1 (α-nuclei excepted as these have

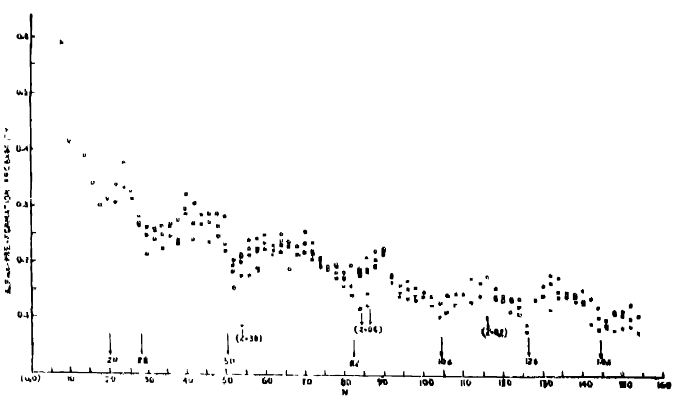

Fig. 1. The dependence of P_α (Theor.) on nuclear mass and nuclear shell-structure.

been exhaustively discussed in a previous work (Basu 1972). There is an unmistakable decreasing trend in P_α with increasing N, starting from $P_\alpha = 0{\cdot}6$ in the light mass-region to $P_\alpha = 0{\cdot}1$ in the heavy mass-region. This mass dependence as well as range of P_α values is, as reported earlier (Basu 1976, 1977), in perfect agreement with the experimental observations of Colli and his co-workers, though not of Chevarier *et al* who observed mass-independence and a lower range of P_α values. The overall decreasing trend of P_α in Fig. 1 is distinctly marked by a few dips easily identifiable with the major neutron shell and sub-shell closure ($N = 20$, 28, 50, 82, (104), 126 and (144)) effects which follow as a natural corollary to mass-dependence. Shell-closure effect was also observed, though only for $N = 126$, by Bonetti & Milazzo-Colli (1974), and Colli-Milazzo *et al* (1975) in their P_α (Expt.) values and also by Mang (1964) in his calculated reduced α-decay width. Becchetti *et al* (1975) also came across pronounced shell-closure effect in the form of reduced α-spectroscopic factor in their study of (d, Li^6) reaction which they rightly attributed to reduction of α-preformation probability at shell-closure. It is no wonder, in view of the lack of rigour of P_α (Expt.) values as already pointed out, that P_α (Expt.) values fail to show up all the major shell and sub-shell closure effects unlike in the present study. But the trend indicates that, with time, P_α (Expt.) will reproduce the present theoretical curve in all its details.

The decreasing trend in the mass-dependence of P_α can be explained in the following terms. High values of P_α in the light-mass region are due to the simple fact that the constituent last two neutrons and last two protons of the α-cluster, being in the same orbit, have a large overlap of their wave-functions due to the high orbital symmetry and yield, consequently a high degree of α-clustering. The low values of P_α in the heavy mass region are the outcome of very low degree of clustering of the last $2n$–$2p$ system as these nucleons occupy, in most cases, two different orbits in the background of increasing Coulomb energy. The gradual decrease of P_α with increasing mass can, in short, be accounted for by the gradual loss of orbital symmetry and a consequently decreasing overlap of the wavefunctions of the last nn- and last pp- pair due to increasing neutron-excess.

The somewhat wavy pattern of P_α vs. N curve in Fig. 1 has its origin, as explained below, in the alternation of sphericity and deformation in nuclear shape caused by the closing and opening, respectively, of the shell (or sub-shell). Nuclei at and in the neighbourhood of closed shells (or sub-shell) are, as is well-known, spherical in shape and are always found to admit of a strict independent-particle shell-model description. The philosophy of the independent-particle shell-model is again diametrically opposed to any type of clustering of nucleons in the nucleus hence one finds an appreciable reduction of α-preformation probability in these spaorical nuclei at and about closed shells (or sub-shells). With the opening of a shell (or a sub-shell), nuclei have more and more extranucleons in the open shell (or sub-shell) which give rise to the long range quadruple force. This quadruple force deforms the nucleus from a spherical shape. Deformation and alpha-preformation also, coincidently enough from Fig 1, are appreciably large for nuclei with extra-core nucleons half-filling the open shell (or sub-shell) compared with neighbouring nuclei. Deformation evidently increases α-preformation probability through enhancement of the overlap of last two neutrons and last two protons wavefunction via admixture of states. Appreciable increase of P_α for nuclei far off closed shells (or sub-shells), clearly present in Fig. 1, was also observed by Colli-Milazzo *et al* (1975) Noticeable enhancements of α-spectroscopic factor of open-shell nuclei for (d, Li^6) reaction led Becchetti *et al* (1975) to conclude that α-clustering is particularyly important for open-shell and permanently deformed nuclei As is evident from Fig. 1, their conclusion is highly justified by the large values of α-preformation probability for these deformed nuclei Deformation effect on P_α is manifest in Fig 1 in a far more systematic and easily identifiable manner than in any of the experimental determinations. Fig 1, in short, demonstrates that, while P_α is a decreasing function of nuclear mass, deformation favours α-preformation to a greater degree than spherical nuclear shape.

Shell-closure evidences in P_α signify that there is probably no more degree of α-clustering in the last $2n$ $2p$ system of an even-even nucleus than is tolerated by the shell-structure, with or without deformation, of a nucleus. An attempt to calculate the present P_α values of different even-even nuclei from a shell model approach will form an interesting study in itself

In the present approach details regarding wave-functions and potentials are side tracked and the α-clustering energy $E^\alpha_{C_l}$ of the last $2n$-$2p$ system inside the parent nucleus is obtained in a straight-forward manner from the mass-relation due to Basu. This yields very accurate value of $E^\alpha_{C_l}$ and hence P_α. E obtained in this way is the effective value of the α-clustering energy. Consequently it contains implicitly all possible correlational effects responsible for α-clustering.

5 Conclusion

The emphasis of the present work has been on a comparative study of up-to-date experimental P_α values and P_α values predicted from the present method. References to the existing literature on α-decay studies have been deliberately kept to a bare minimum as most of this literature deals with the reduced α-decay width rather than with the absolute α-preformation probability and is, therefore, incapable of commenting on experimental P_α values.

In this study it has been shown that P_α (Expt.) of even-even nuclei is correct so far as the order of magnitude is concerned and that the absolute α-preformation probability expression in the *α-decay without tunnelling* picture is a very reliable one for the evaluation of absolute P_α It is expected that P_α (Expt.) values with further refinement in the method of analysis and improvement in the accuracy of experimental input data, will come to a perfect agreement with the predictions of the present approach Present investigation amply demonstrates that α-preformation probability is a decreasing function of nuclear mass and reveals also the effect of shell and sub-shell closures and deformation in nuclear shape on α-preformation probability *A priori* knowledge of absolute α-preformation probability obtainable from this method will facilitate some aspects of nuclear structure analysis, and will also help improve upon the existing theories of α-emission, α-pick-up and α-transfer reactions.

Acknowledgment

Thanks are due Professor P. C Bhattacharya for his kind interest in this work. The U. G. C., Government of India, is also thanked for financial support

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